

## SUBSTITUTE SPECIFICATION

### PROCESS FOR TREATING COMPRESSION IGNITION ENGINE EXHAUST GAS

This application is the U.S. National Phase application of PCT International Application No. PCT/GB2004/004218, filed October 5, 2004, and claims priority of British Patent Application No. 0323386.3, filed October 7, 2003.

### FIELD OF THE INVENTION

The present invention relates to a process for treating exhaust gases from a compression ignition engine and in particular, an engine wherein substantially all fuel for combustion is injected into a combustion chamber prior to start of combustion.

### BACKGROUND OF THE INVENTION

Conventional diesel engines produce less gaseous hydrocarbon (HC) and carbon monoxide (CO) than gasoline engines and it is possible to meet present legislated limits for these components using a platinum (Pt)-based diesel oxidation catalyst (DOC). Diesel nitrogen oxides (NO<sub>x</sub>) emissions are presently controlled by engine management, such as exhaust gas recirculation (EGR). As a consequence, however, diesel particulate matter (PM) emissions including volatile and soluble organic fractions (VOF and SOF respectively) are increased. The DOC is used to treat VOF and SOF in order to meet presently legislated limits for PM.

Two ways of reducing compression ignition engine emissions, which can be used in addition to exhaust gas after treatment, are engine management and engine design. More recently, a new generation of compression ignition engines have been developed which use a range of engine management techniques to lower the combustion temperature.

- 5 One such technique is for substantially all fuel for combustion to be injected into a combustion chamber prior to the start of combustion.

An advantage of these techniques is that they can reduce  $\text{NO}_x$  and PM emissions, without significantly increasing fuel consumption. An embodiment of the new generation  
10 of engines which employs these techniques is known as a Homogeneous Charge Compression Ignition (HCCI) diesel engine. Characteristics of an HCCI diesel engine include homogeneous fuel charge for external or internal mixture formation by variable valve timing, increased swirl ratio, injection rate control (multiple injection) and adapted spray configuration; high dilution rate for a moderate burn rate; low  $\text{NO}_x$  by charge  
15 dilution and low combustion temperature; and low PM by prolonging the time for mixture preparation and, consequently, homogenisation. All relative terms are compared to a normal direct injection diesel engine.

Another new compression ignition engine is known as the Dilution Controlled  
20 Combustion System (DCCS), for example Toyota's Smoke-less Rich Combustion concept. Characteristics of DCCS include conventional direct injection; extremely high dilution rate to lower combustion temperature below soot formation threshold by increasing ignition lag, increase in swirl ratio, variable valve timing and injection rate control (multiple injection); low  $\text{NO}_x$  and PM by very high charge dilution rate and extremely low  
25 combustion temperature; and very high EGR rate. All relative terms are compared to a normal direct injection diesel engine.

By contrast, a typical direct injection light-duty diesel engine produces approximately 50ppm  $\text{NO}_x$ , 1000ppm CO and 800ppm HC (C1) at idle (exhaust gas

temperature about 185°C); and approximately 1250ppm NO<sub>x</sub>, 70ppm CO and 30ppm HC (C1) at high load (exhaust gas temperature about 500°C (all values engine out)).

We have investigated the emissions of a vehicle including one of the new generation of engines, and have found that, despite the improvements in reduced NO<sub>x</sub> and PM, they can produce high levels of CO relative to a conventional direct injection diesel engine. Such CO emissions can be characterised by an exhaust gas composition of >2000ppm CO, such as >2500-10000ppm CO e.g. >3000ppm CO, >4000ppm CO, >5000ppm CO, >6000ppm CO, >7000ppm CO, >8000ppm CO or >9000ppm CO, below e.g. about 250°C during conditions wherein substantially all fuel for combustion is injected into a combustion chamber prior to the start of combustion.

Additionally, we have observed that such diesel engines can produce a relatively high level of HC below e.g. about 250°C, e.g. less than 200°C or less than 150°C, during low NO<sub>x</sub> operating conditions, such as >500ppm e.g. from 600-1000ppm, illustratively 700ppm HC, 800ppm HC or 900ppm HC, C<sub>1</sub> unburned hydrocarbon (HC).

Furthermore, we believe that unsaturated hydrocarbons can result from the incomplete combustion of diesel fuel, examples of which are ethylene, propylene, aromatics and polyaromatics. Release of certain unsaturated HCs is undesirable for environmental and health reasons.

It is known that current direct injection diesel engines can produce exhaust gas comprising >2000ppm CO under certain operating conditions, e.g. at cold start as part of a warm-up strategy or following hard acceleration. However, we believe that the current diesel engines do not emit such high levels of CO under normal driving conditions or such high levels of CO in combination with such high levels of HC during normal operation, e.g. at temperatures of up to 250°C.

In our EP 0341832 we disclose a process for combusting diesel particulate deposited on a filter in nitrogen dioxide ( $\text{NO}_2$ ) at up to  $400^\circ\text{C}$ , which  $\text{NO}_2$  is obtained by oxidising nitrogen monoxide ( $\text{NO}$ ) in the exhaust gas over a suitable catalyst disposed upstream of the filter. The  $\text{NO}$  oxidation catalyst can comprise a platinum group metal (PGM) such as Pt, palladium (Pd), ruthenium (Ru), rhodium (Rh) or combinations thereof, particularly Pt. The filter can be coated with material which facilitates higher temperature combustion such as a base metal catalyst, e.g. vanadium oxide,  $\text{La/Cs/V}_2\text{O}_5$  or a precious metal catalyst. Such a system is marketed by Johnson Matthey as the CRT<sup>®</sup>.

We have now identified a family of catalysts that are particularly effective in converting relatively high levels of CO in exhaust gas produced by the new generation of compression ignition engine, particularly at temperatures below about  $250^\circ\text{C}$ . Our research also shows that these catalysts are more effective at treating certain HC than Pt DOC alone in exhaust gas comprising relatively high levels of CO, for example at temperatures below about  $250^\circ\text{C}$ . Indeed, we have found evidence of synergy for treating HC, including unsaturated HC, in systems comprising both Pt and Pd.

#### SUMMARY OF THE INVENTION

According to one aspect, the invention provides a process for treating exhaust gas from a compression ignition engine, wherein substantially all fuel for combustion is injected into a combustion chamber prior to the start of combustion, which process comprising contacting the exhaust gas with a catalyst comprising a supported palladium (Pd) catalyst.

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By "metal" herein, we mean the oxidic compound existing in the presence of the constituents of exhaust gas, although in use they may be present as the nitrate, carbonate or hydroxide.

In one embodiment, the catalyst comprises at least one base metal promoter.

In another embodiment, the exhaust gas comprises  $>2000\text{ppm CO}$ .

5        In a further embodiment, the exhaust gas comprises  $>500\text{ppm C}_1$  unburned hydrocarbons (HCs) and optionally is at below  $250^\circ\text{C}$ .

In a further embodiment, the catalyst comprises Pt, and it is preferably arranged so that the exhaust gas contacts the Pd catalyst and then contacts the Pt.

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In a further embodiment, combustion of CO in the exhaust gas over the Pd creates an exotherm to heat the Pt, thereby promoting reactions of exhaust gas components catalysed by the Pt, including HC oxidation and combustion of PM.

15        According to a further aspect, the invention provides a compression ignition engine wherein substantially all fuel for combustion is injected into a combustion chamber prior to the start of combustion, which engine comprising an exhaust system comprising a supported palladium (Pd) catalyst.

20        According to one embodiment, the catalyst comprises at least one base metal promoter.

According to another embodiment, the engine produces exhaust gas comprising  $>2000\text{ppm CO}$ .

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According to one embodiment, the engine produces exhaust gas comprising  $>500\text{ppm C}_1$  unburned hydrocarbons (HC).

According to another embodiment, the engine produces exhaust gas including the defined amounts of CO and/or HC at an exhaust gas temperature of below about 250°C.

#### DETAILED DESCRIPTION OF THE INVENTION

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In a particular embodiment, depending on the exhaust gas composition produced by the engine, it can be useful to include Pt on the same support as the Pd or a different support. Pt can be particularly useful for oxidising unsaturated HCs, and is, of course, used as a major component of conventional DOCs for treating VOF and SOF. Hence an advantage of a catalyst for use in the invention comprising both Pd and Pt is that it can  
10 treat a wider range of HC. One reason for this is that an exotherm generated by the Pd component in the CO can increase the temperature of the Pt component to above its HC light-off temperature.

15 The at least one base metal promoter for the Pd catalytic component can be a reducible oxide or a basic metal or a mixture of any two or more thereof. Illustrative examples of reducible oxides are at least one of manganese, iron, tin, copper, cobalt and cerium, such as at least one of  $\text{MnO}_2$ ,  $\text{Mn}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{SnO}_2$ ,  $\text{CuO}$ ,  $\text{CoO}$  and  $\text{CeO}_2$ . The reducible oxide can be dispersed on a suitable support and/or the support *per se* can  
20 comprise particulate bulk reducible oxide. An advantage of  $\text{CeO}_2$  is that it is relatively thermally stable, but it is susceptible to sulfur poisoning. Manganese oxides are not as thermally stable, but they are more resistant to sulfur poisoning. Manganese oxide thermal stability can be improved by combining it in a composite oxide or mixed oxide with a stabiliser, such as zirconium. To some extent, ceria can be made more sulfur tolerant by  
25 forming a composite oxide or a mixed oxide with a suitable stabiliser, such as zirconium.

By "reducible oxide" herein, we mean that an oxide is present *in situ* wherein the metal has more than one oxidation state. In manufacture, the metal can be introduced as a non-oxide compound and oxidised by calcinations to the reducible oxide.

The basic metal can be an alkali metal, e.g. potassium, sodium or caesium, an alkaline earth metal, such as barium, magnesium, calcium or strontium, or a lanthanide metal, e.g. cerium, praseodymium or lanthanum, or any mixture, composite oxide or mixed oxide of any two or more thereof. In systems comprising two or more basic metal promoters, it is desirable to prevent interaction between the basic metals. Accordingly, it is preferred that no more than 3wt% of the Pd catalyst comprises basic metal promoter.

In one embodiment, the basic metal is ceria, and the Pd is supported on particulate ceria, i.e. the particulate ceria serves as the Pd support and promoter.

Alternatively, the support for the or each PGM can be any conventional support known in the art such as alumina, magnesia, silica-alumina, titania, zirconia, a zeolite or a mixture, composite oxide or mixed oxide of any two or more thereof, and can be doped, as conventional in the art with a basic metal. Non-limiting examples of the basic metal dopants are zirconium, lanthanum, alumina, yttrium, praseodymium, cerium, barium and neodymium. The support can be, for example, lanthanum-stabilised alumina, or a composite oxide or a mixed oxide comprising ceria and zirconia, optionally in a weight ratio of from 5:95 to 95:5.

"Composite oxide" as defined herein means a largely amorphous oxide material comprising oxides of at least two elements which are not true mixed oxides consisting of the at least two elements.

Suitable mixed oxides and composite oxides for the present invention may be prepared by conventional means, namely co-precipitation. For example, solutions of soluble salts of the metals may be mixed in the appropriate concentrations and amounts to yield the desired end product, then caused to precipitate concurrently, for example by adding a base such as ammonium hydroxide. Alternatively, other preparative routes

utilising generally known technology, such as sol/gel or gel precipitation, have been found suitable. The precipitated oxides as slurries may be filtered, washed to remove residual ions, dried, then fired or calcined at elevated temperatures ( $>450^{\circ}\text{C}$ ) in air.

- 5           A 85Mn:15Zr composite oxide material can be prepared as follows. Manganese nitrate (121.76g, 0.425mol) and aluminium nitrate (28.14g, 0.075mol) are dissolved in demineralised water to give 400ml of solution. This solution was added carefully over two minutes to an overhead stirred ammonia solution (150ml, 2.25mol diluted to 500ml). The precipitate slurry was stirred for five minutes and then allowed to 'age' for thirty minutes.
- 10   The precipitate was recovered by filtration and washed until the conductivity of the filtrate was  $1500\mu\text{Scm}^{-1}$ . The material was dried at  $100^{\circ}\text{C}$  and then fired at  $350^{\circ}\text{C}$  for two hours (ramp up and down  $10^{\circ}\text{C}/\text{min}$ ).

- The catalyst can contain from 0.1 to 30% by weight, optionally from 0.5-15% and preferably 1-5%, of PGM based on the total weight of the catalyst. In one embodiment, the catalyst contains a weight ratio of from 100:0 to 10:90 Pd:Pt. In a further embodiment, the catalyst contains from 0.1 to 10% Pt by weight based on the total weight of the catalyst and from 0.1 to 20% by weight based on the total weight of the catalyst. According to a further embodiment, the exhaust system comprises from 30-300 $\text{gft}^{-3}$  Pd and, where
- 20   present, from 30-300 $\text{gft}^{-3}$  Pt.

- The catalytic converter can comprise a conventional substrate, such as a ceramic, e.g. cordierite, or metal, e.g. Fecralloy<sup>TM</sup>, honeycomb monolith. In a particular embodiment, one or both substrates comprise a particulate filter, such as a ceramic wall
- 25   flow filter e.g. the upstream substrate can be a flow through substrate and the downstream substrate a filter. The catalyst can be coated on a downstream end of the filter, if desired. Where the sole platinum group metal (PGM) present is Pd, a single substrate can be coated with a washcoat including the supported Pd and the at least one base metal promoter.



However, where the catalyst includes also Pt, we envisage that the catalytic converter can take one of several forms.

5 In one embodiment, both the Pd and the Pt is supported on the same particulate support material.

10 In another embodiment, comprising a single substrate, the supported Pd and the at least one base metal promoter are coated on an upstream part of the substrate and the Pt is coated on a downstream part thereof, although the Pt can be upstream of the Pd if desired.

10 In an alternative embodiment, also comprising a single substrate, the Pt is disposed in a first layer on the substrate and the supported Pd and the at least one base metal promoter are disposed in a second layer overlying the first layer. However, if desired, the Pt can be in the over layer and the Pd in the under layer.

15 In a fourth embodiment also comprising a single substrate, the substrate is coated with a single washcoat layer, wherein the supported Pd and the at least one base metal promoter comprise a first particulate support and the Pt is carried on a second particulate support, wherein the first and second supports are disposed on a substrate in a single layer.

20 In an alternative embodiment, the exhaust system comprises a first substrate comprising the supported Pd and the at least one base metal promoter and a second substrate comprising the Pt, which second substrate is disposed downstream of the first substrate. The order of the first and second substrates can be reversed, if desired.

25 In the new generation of diesel engine-installed vehicles, the engines may be controlled to operate in a mode wherein substantially all fuel for combustion is injected into a combustion chamber prior to the start of combustion over the entire engine load-speed map. However, we envisage that in a particular embodiment, the engine control

means can switch the engine to more conventional diesel combustion as is used in direct injection diesel engines at high loads. During such periods of "direct injection" running, levels of  $\text{NO}_x$  and PM can require treatment in order for the vehicle as a whole to meet the relevant emission legislation.

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According to a particular embodiment, the invention provides an engine according to the invention having a first running condition wherein the engine is configured to run during at least one portion of an engine cycle in a mode wherein substantially all fuel for combustion is injected into a combustion chamber prior to the start of combustion, and a  
10 second condition wherein the engine is configured to run in a conventional direct injection diesel engine mode. Control of the first and second running conditions can be effected by an engine control means associated with the engine e.g. comprising a pre-programmed processor such as a central processor unit (CPU), optionally forming part of the engine control unit (ECU).

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Where additional exhaust gas after-treatment is required in order to treat exhaust gas during the second running condition, an optionally catalysed particulate filter can be disposed downstream of the Pd catalyst and associated at least one base metal promoter an, where present, the Pt catalyst. Such an arrangement is described in our EP 0341832,  
20 wherein NO in the exhaust gas is oxidised to  $\text{NO}_2$  by the Pd catalyst and particulates in the exhaust gas collected on the filter are combusted in the  $\text{NO}_2$  at temperatures of up to  $400^\circ\text{C}$ . The Pt catalyst can be disposed on the filter, as desired.

Where the engine according to the invention includes an exhaust gas recirculation  
25 valve and a circuit to recirculate a selected portion of the exhaust gas to the engine air intake, desirably the exhaust gas is cooled prior to mixing with the engine intake air.

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The compression ignition engine according to the invention can be a diesel engine, for example, such as a light-duty diesel engine or a heavy-duty diesel engine, as defined by the relevant legislation.

5 Two embodiments of engines with which the exhaust system of the invention may be used with advantage are a homogeneous charge compression ignition (HCCI) diesel engine and a Dilution Controlled Combustion System (DCCS) diesel engine.

10 According to a further aspect, the invention provides a vehicle including an engine according to the invention.

## EXAMPLES

15 In order that the invention may be more fully understood reference is made to the following Examples by way of illustration only. All temperatures given refer to inlet gas temperatures.

### EXAMPLE 1

20 A 2wt% Pt-alumina-based catalyst (Catalyst A), a 2wt% Pd-alumina-based catalyst (Catalyst B), and a 2wt% Pd-ceria-containing catalyst (Catalyst C) were tested for HC and CO light-off in a simulated catalyst activity test (SCAT) gas rig. A sample of each catalyst was tested in the flowing gas mixtures set out in Table 1. The temperature of the gas mixtures used was increased during each test from 100°C to 500°C.

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**Table 1: Gas mixtures used for activity tests for Catalysts A, B, and C**

	<b>Gas Mixture 1</b>	<b>Gas Mixture 2</b>	<b>Gas Mixture 3</b>	<b>Gas Mixture 4</b>
ppm HC (C1) as propene	600	900	3000	3000
ppm CO	200	600	25000	25000
ppm NO	200	200	200	200
% H <sub>2</sub> O	4.5	4.5	4.5	4.5
% O <sub>2</sub>	12	12	12	3
% CO <sub>2</sub>	4.5	4.5	4.5	4.5
ppm SO <sub>2</sub>	20	20	20	20
N <sub>2</sub>	Balance	Balance	Balance	Balance
Flow Rate (litres/hour/g sample)	300	300	300	300
Ramp Rate (°C/min)	10	10	10	10

- Gas mixtures 1 and 2 have HC and CO gas concentrations as typical of exhaust gases from a conventionally operated Diesel engine. Gas mixture 3 has higher HC and CO concentrations than gas mixtures 1 and 2 and gas mixture 4 has a lower oxygen concentration than used in gas mixtures 1 to 3. Tables 2 and 3 show the temperature at which 80% oxidation conversion of HC and CO was achieved over each catalyst.

**Table 2: Temperature for 80% conversion (T<sub>80</sub> HC/CO) of Catalysts A, B and C in gas mixtures 1-3.**

<b>T<sub>80</sub> HC / CO (°C)</b>	<b>Gas Mixture 1</b>	<b>Gas Mixture 2</b>	<b>Gas Mixture 3</b>
Catalyst A	170 / <110	158 / 114	185 / 183
Catalyst B	264 / 265	253 / 247	205 / 203
Catalyst C	231 / 164	226 / 170	< 110 / <110

- Catalyst A showed significantly higher activity than Catalyst B or C at lower temperatures for both HC and CO oxidation using the gas mixtures 1 and 2, but showed a loss in low temperature oxidation activity in the high HC and CO gas mixture 3. In contrast to the loss in activity in high HC, CO gas feeds for Catalyst A, Catalyst B showed

a small improvement in low temperature oxidation activity from gas mixture 1 or 2 to gas mixture 3. However, despite the improved low temperature activity of Catalyst B for the higher HC and CO gas feed conditions, overall the activity of Catalyst B was poorer than that of Catalyst A. By contrast, Catalyst C showed lower activity under gas mixtures 1 and 2 relative to Catalyst A. However, in contrast to Catalyst A and Catalyst B, Catalyst C showed the highest activity for HC and CO oxidation at low temperatures under the high HC and CO gas concentration mixture 3.

Table 3 shows that the low temperature CO activity of Catalyst A was further decreased in gas mixture 4, consisting of 3% oxygen, compared to the activity measured in gas mixture 3, which included 12% oxygen. In contrast, the activity of Catalyst B was slightly improved in gas mixture 4 compared to gas mixture 3. The low temperature oxidation activity of Catalyst C remained very high in both gas mixtures 3 and 4. The data show that Pd is more active in the presence of CO than Pt.

**Table 3: Temperature for 80% conversion (T80-CO) of Catalysts A, B and C in gas mixtures 3 and 4**

T80 CO (°C)	Mixture 3	Mixture 4
Catalyst A	183	239
Catalyst B	203	197
Catalyst C	<110	<110

### **EXAMPLE 2**

In another series of activity tests, Catalyst D (1wt% Pt-alumina-based), and Catalyst E (4wt% Pd-ceria-based), were tested for HC and CO light-off in a SCAT gas rig using the gas mixtures set out in Table 4, and the temperature of the gas passed over each sample was increased during each test from 100°C to 500°C.

**Table 4: Gas mixtures used for activity tests of Catalysts D and E**

	<b>Gas Mixture 5</b>	<b>Gas Mixture 6</b>	<b>Gas Mixture 7</b>	<b>Gas Mixture 8</b>	<b>Gas Mixture 9</b>
ppm HC (C1) as toluene	600	600	600	600	600
ppm CO	200	950	2000	10000	25000
ppm NO	200	200	200	200	200
% H <sub>2</sub> O	4.5	4.5	4.5	4.5	4.5
% O <sub>2</sub>	12	12	12	12	12
% CO <sub>2</sub>	4.5	4.5	4.5	4.5	4.5
ppm SO <sub>2</sub>	20	20	20	20	20
N <sub>2</sub>	Balance	Balance	Balance	Balance	Balance
Flow Rate (litres/hour/g sample)	300	300	300	300	300
Ramp Rate (°C/min)	10	10	10	10	10

For each gas mixture from 5 to 9, the CO concentration was progressively increased and the remaining gases were kept constant with a nitrogen balance. Table 5 shows the effect of CO concentration on the HC and CO light-off of the catalysts.

**Table 5: Temperature for 80% conversion (T80-HC/CO) of Catalysts D and E in gas mixtures 5-9.**

<b>T80 HC / CO (°C)</b>	<b>Gas Mixture 5</b>	<b>Gas Mixture 6</b>	<b>Gas Mixture 7</b>	<b>Gas Mixture 8</b>	<b>Gas Mixture 9</b>
Catalyst D	188/112	192/158	194/185	212/210	231/217
Catalyst E	259/135	256/130	175/<110	<110/<110	<110/<110

Catalyst D showed a loss in low temperature activity as the CO concentration was progressively increased, whereas Catalyst E showed improved low temperature activity with higher CO gas feeds. We infer that the loss in activity for Catalyst D is because of self-poisoning of the active sites on the catalyst. It is well known that the strong adsorption of CO on the Pt active sites may block the adsorption of oxygen necessary for the oxidative reaction to form CO<sub>2</sub>. Catalyst E does not show this self-poisoning

behaviour, and the activity of this catalyst to oxidise CO in higher CO concentrations is significantly improved over Catalysts A and D.

### **EXAMPLE 3**

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Further SCAT rigs tests on Catalyst D (1wt% Pt-alumina-based) and Catalyst E (4wt% Pd-ceria-based) were carried out using the gas mixtures with 25000ppm CO and two different HC concentrations (using either propene or toluene). A sample of each catalyst was placed in the gas mixtures shown in Table 6, and the temperature of the gas was increased from 100°C to 500°C. The concentration of HC (as C1) was increased from 600ppm to 3000ppm using either propene or toluene as the HC species. The activity of the catalysts tested is given in Table 7.

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**Table 6: Gas mixtures used for activity tests on Catalyst A and Catalyst C**

	<b>Gas Mixture 10</b>	<b>Gas Mixture 11</b>	<b>Gas Mixture 12</b>	<b>Gas Mixture 13</b>
ppm HC (C1) as propene	600	3000	0	0
ppm HC (C1) as toluene	0	0	600	3000
ppm CO	25000	25000	25000	25000
ppm NO	200	200	200	200
% H <sub>2</sub> O	4.5	4.5	4.5	4.5
% O <sub>2</sub>	12	12	12	12
% CO <sub>2</sub>	4.5	4.5	4.5	4.5
ppm SO <sub>2</sub>	20	20	20	20
N <sub>2</sub>	Balance	Balance	Balance	Balance
Flow Rate (litres/hour/g sample)	300	300	300	300
Ramp Rate (°C/min)	10	10	10	10

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**Table 7: Temperature for 80% conversion (T80-CO/HC) of catalysts D and E in gas mixtures 10-13**

T80 HC/CO (°C)	Gas Mixture 10	Gas Mixture 11	Gas Mixture 12	Gas Mixture 13
Catalyst D	186/184	218/218	231/217	230/231
Catalyst E	<110/<110	<110/<110	<110/<110	<110/<110

For gas mixtures 10 and 12 (containing 25000ppm CO, 600ppm HC), Catalyst E showed the highest activity for HC and CO light-off. The light-off activity of Catalyst D deteriorated in gas mixtures 11 and 13 (containing 25000ppm CO, 3000ppm HC) relative to the activity found for gas mixtures 10 or 12. The activity of Catalyst E in all the gas mixtures used remained higher than that of Catalyst D.

#### **EXAMPLE 4**

Further SCAT rig tests on Catalyst A, Catalyst B, and Catalyst C were carried out using gas mixtures with 10000ppm CO and four different HC concentrations (using propene). A sample of each catalyst was tested in the gas mixtures in Table 8, and the temperature of the gas was increased from 100°C to 500°C. The concentration of HC (as C1) was increased from 600ppm to 4500ppm (propene). The activity of the catalysts is shown in Table 9.



**Table 8: Gas mixtures used for activity tests of Catalysts A, B and Catalyst C**

	Gas Mixture 14	Gas Mixture 15	Gas Mixture 16	Gas Mixture 17
ppm HC (C1) as propene	600	1800	3000	4500
ppm CO	10000	10000	10000	10000
ppm NO	200	200	200	200
% H <sub>2</sub> O	4.5	4.5	4.5	4.5
% O <sub>2</sub>	12	12	12	12
% CO <sub>2</sub>	4.5	4.5	4.5	4.5
ppm SO <sub>2</sub>	20	20	20	20
N <sub>2</sub>	Balance	Balance	Balance	Balance
Flow Rate (litres/hour/g sample)	300	300	300	300
Ramp Rate (°C/min)	10	10	10	10

**Table 9: Temperature for 80% conversion (T<sub>80</sub>-CO/HC) of Catalysts A, B and C in gas mixtures 14-17.**

C <sub>3</sub> H <sub>6</sub> ppm	Catalyst A		Catalyst B		Catalyst C	
	CO T <sub>80</sub>	C <sub>3</sub> H <sub>6</sub> T <sub>50</sub>	CO T <sub>80</sub>	C <sub>3</sub> H <sub>6</sub> T <sub>50</sub>	CO T <sub>80</sub>	C <sub>3</sub> H <sub>6</sub> T <sub>50</sub>
600	159	156	169	176	121	<110
1800	159	165	179	177	130	134
3000	161	162	179	177	136	135
4500	161	170	180	179	133	142

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Catalyst C exhibits the highest activity for HC and CO oxidation in the gas feed that contained 600ppm HC. Catalyst B had the poorest activity. Increased levels of HC caused a slight drop in catalyst activity, but even at the highest HC levels Catalyst C had much lower temperature activity for oxidation light-off compared to Catalysts A and B.

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### **EXAMPLE 5**

A further series of SCAT tests with Catalyst C (2wt% Pd-ceria), Catalyst F (2.5 wt% Pt-alumina-based) and Catalyst G (1.25wt% Pt/1wt% Pd - which is a mixture of

Catalyst C and Catalyst F) were conducted using gas mixtures with 1% CO and three different HC species at 1000ppm (C3) concentration. The test procedure was as described in Example 1 above and the gas mixtures are shown in Table 10. The activity of the catalysts tested is given in Table 11.

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**Table 10: Gas mixtures used for activity tests on Catalysts C, F & G**

	Gas Mixture 18	Gas Mixture 19	Gas Mixture 20
ppm HC (C3) as propene	1000	0	0
as ethene	0	1000	0
as ethane	0	0	1000
ppm CO	10,000	10,000	10,000
ppm NO	200	200	200
%H <sub>2</sub> O	4.5	4.5	4.5
%O <sub>2</sub>	12	12	12
%CO <sub>2</sub>	4.5	4.5	4.5
ppm SO <sub>2</sub>	20	20	20
N <sub>2</sub>	Balance	Balance	Balance
Flow Rate (litres/hour/g sample)	300	300	300
Ramp Rate (°C/min)	10	10	10

**Table 11: Temperature for 80% and 50% conversion (CO/HC) of Catalysts C, F, and G in gas mixtures 18, 19 and 20.**

HC Species	Catalyst C		Catalyst F		Catalyst G	
	CO <sub>T80</sub>	HC <sub>T50</sub>	CO <sub>T80</sub>	HC <sub>T50</sub>	CO <sub>T80</sub>	HC <sub>T50</sub>
C <sub>3</sub> H <sub>6</sub>	136	135	161	162	137	139
C <sub>2</sub> H <sub>4</sub>	<110	186	160	167	129	127
C <sub>2</sub> H <sub>6</sub>	<110	367	159	301	137	303

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Whilst Catalyst C remains highly effective for CO oxidation at low temperature, Catalyst F remains more effective for small chain HC oxidation except for propene. The mixed system Catalyst G showed good CO activity with not dissimilar activity to Catalyst C. Catalyst G showed equivalent propene light off to Catalyst C and considerably lower

light off for ethene and ethane, demonstrating the strong synergistic effect achieved by combining both catalyst formulations.

### EXAMPLE 6

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The effect of other metal supports was assessed for comparison with Catalyst A (2wt% Pd - Al<sub>2</sub>O<sub>3</sub>) and Catalyst C (2wt% Pd-Ce) in gas mixture 3 (high CO and HC concentrations) and gas mixture 21 (low CO and HC concentrations). Additional catalysts evaluated were Catalyst H (2wt% Pd-MnO<sub>2</sub> (Aldrich)), Catalyst I (2wt% Pd-Mn:Zr  
10 [85.15]) and Catalyst J (2 wt% Pd - 20% Ba/Al<sub>2</sub>O<sub>3</sub>). The test procedure was as before and gas mixtures are shown in Table 12, with catalyst activity summarised in Table 13.

**Table 12: Gas mixtures used for activity tests on Catalyst A, C, H, I, and J.**

	Gas Mixture 21	Gas Mixture 3
ppm HC (C1) as propene	900	3000
ppm CO	1000	25000
ppm NO	200	200
% H <sub>2</sub> O	4.5	4.5
% O <sub>2</sub>	12	12
% CO <sub>2</sub>	4.5	4.5
ppm SO <sub>2</sub>	20	20
N <sub>2</sub>	Balance	Balance
Flow Rate (litres/hour/g sample)	300	300
Ramp Rate (°C/min)	10	10

15 **Table 13: Temperature for 80% and 50% conversion (CO/HC) of Catalysts A, C, H, I and J in gas mixtures 3 and 21.**

Catalyst	Gas Mixture 21		Gas Mixture 3	
	CO T <sub>80</sub>	HC T <sub>50</sub>	CO T <sub>80</sub>	HC T <sub>50</sub>
A	230	230	183	176
C	175	200	<110	<110
H	<110	159	<110	<110
I	152	189	<110	<110
J	202	211	167	160

- Both Mn containing catalysts H and I show equivalent performance to Catalyst C with high CO concentrations but also lower light off with low CO concentrations. Addition of Ba (Catalyst J) shows improved performance with high CO compared to low
- 5 CO concentration and has superior activity compared to Catalyst A.

### **EXAMPLE 7**

- A 1.9 litre, common rail, direct injection, turbo charged, diesel vehicle certified for
- 10 European Stage 3 legislative requirements, and fuelled with < 10ppm sulphur-containing diesel fuel, was fitted with ceramic supported catalysts 4.66in (118mm) diameter and 6in (152mm) long. Catalyst K was coated with platinum catalyst at  $140\text{ g ft}^{-3}$  ( $4.85\text{ g litre}^{-1}$ ) and Catalyst L was coated with platinum catalyst at  $70\text{ g ft}^{-3}$  ( $2.43\text{ g litre}^{-1}$ ) and palladium-ceria catalyst at a palladium loading of  $70\text{ g ft}^{-3}$  ( $2.43\text{ g litre}^{-1}$ ). Before testing, the catalysts were
- 15 aged for 5 hours at  $700^{\circ}\text{C}$ .

- The engine exhaust emissions were modified to reproduce a range of exhaust gas conditions. These variations were achieved by allowing one or more of the following parameters to be changed: EGR rate, pilot injection timing and quantity of fuel injected,
- 20 main injection timing, common rail fuel pressure and boost pressure of the turbo charger. With these calibration changes it was possible to increase HC and CO levels from the engine.

- Both catalysts were evaluated in the European three-test cycle with the standard
- 25 production calibration (Base). They were then evaluated with a calibration which produced CO emissions three times higher than the base calibration. Table 14 summarises the results for both catalysts with both calibrations.

**Table 14: Results (g/km) with Catalyst A and B for both calibrations.**

		g/km	
		Catalyst K (Pt)	Catalyst L (Pt + Pd)
<b>Base Calibration</b>	Engine Out HC	0.19	0.21
	Engine Out CO	1.43	1.42
	Engine Out NOx	0.38	0.38
	Tailpipe HC	0.014	0.009
	Tailpipe CO	0.042	0.041
	Tailpipe NOx	0.37	0.38
<b>High CO Calibration</b>	Engine Out HC	0.39	0.39
	Engine Out CO	4.55	4.28
	Engine Out NOx	0.72	0.78
	Tailpipe HC	0.122	0.08
	Tailpipe CO	1.58	0.398
	Tailpipe NOx	0.73	0.77

From Table 14 it can be seen that with the Base Calibration the catalysts have very similar performance with regard to CO removal. With the high CO calibration the Catalyst

- 5 L has much lower tailpipe HC and CO emissions than Catalyst K.

The method used to increase the CO emissions from the engine also resulted in a noticeable increase in NO<sub>x</sub>. This would not occur in the type of engine designed specifically to operate under conditions which would result in these high CO emissions.

- 10 However, the results show that the oxidation performance of both catalysts is independent of NO<sub>x</sub> concentration. Therefore, using a constant concentration of 200ppm NO<sub>x</sub> in the synthetic gas test had no influence on the results obtained for HC and CO oxidation.